Hydraulic Evaluation of a Lock Conduit Experiencing Structural Failure

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Abstract

A hydraulic analysis of the Whitten Lock filling and emptying system was performed. The Whitten Lock, located on the Tennessee-Tombigbee Waterway, is a high-head structure having a design lift of 84 ft. Evaluation of the culvert system was considered necessary because the lock's structure has experienced damage over the past years on the roof of the crossover culvert. The purpose of this study was to determine whether or not the hydraulic conditions were significantly different from those anticipated during the design process and whether or not these hydraulic conditions were causing the damage to the crossover roof. A numerical model study of the lock provided peak velocities and pressure differences throughout the filling and emptying system. A one-dimensional model of the entire culvert system including the flow control valves was used in conjunction with a three-dimensional model of the geometrically complex crossover culverts where the damage has occurred. The numerical model results indicated that the hydraulic conditions were not significantly different from those observed in the hydraulic model study conducted during the project's design phase. The current study also investigated the hydraulic consequences of various filling and emptying operations.

Introduction

Whitten Lock and Dam is the uppermost navigation structure on the Tennessee-Tombigbee Waterway. The lock, which was initially named Bay Springs Lock, was officially opened to navigation in May 1985. The lock chamber is nominally 600 ft long (pintle to pintle) by 110 ft wide. At normal upper and lower pools, the lock has a lift of 84 ft. The filling and emptying system is a bottom longitudinal floor culvert system commonly referred to as an "H" system. Details of the filling and emptying system are provided on the plan and elevation drawing of Figure 1.

The culvert system consists of 10-port intake manifolds on either lock wall from which the flow transitions to 14-ft by 14-ft culverts in each wall. Reverse tainter valves are used to control both the filling and emptying flow in these main culverts. Dual 12-in. diameter ducts are provided to introduce air downstream of each filling

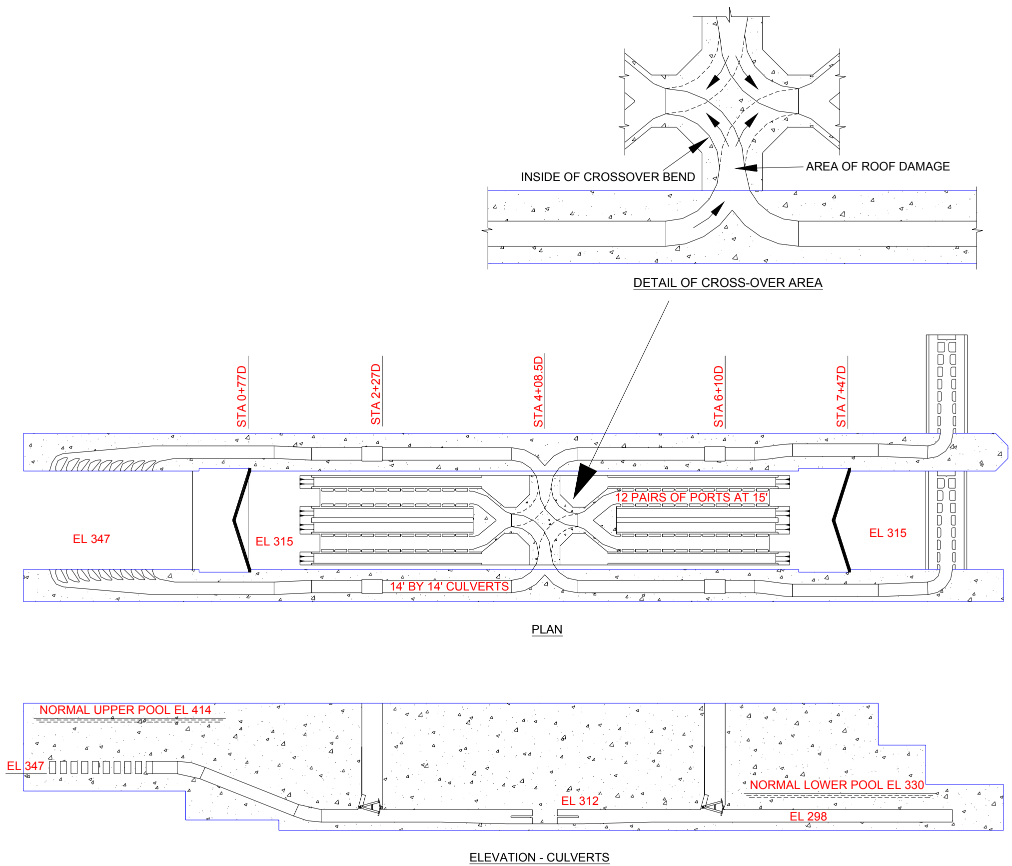

Figure 1. Plan and profile of Whitten Lock

and emptying valve. The crossover culvert vertically splits the flow with a horizontal splitter plate in each main culvert thus dividing the flow into each half of the chamber. The flow is then split horizontally to feed 2 longitudinal filling and emptying manifolds in each half of the chamber. These longitudinal manifolds each have 12 pairs of 3.5-ft-tall by 1.5-ft-wide ports. Each main culvert of the emptying system terminates at a lateral manifold. These manifolds each have 8 pairs of 6-ft tall by 3-ft wide ports.

Problem

A hydraulic evaluation of the culvert system was considered necessary because the lock structure has experienced significant damage over the past years on the roof of the crossover where the right culvert enters the lock chamber (Figure 1). The concrete roof has eroded several inches deep for a distance of 20 ft or so towards the center of the lock. This area has experienced damage before and was repaired in 1996 and again in 2001. A section of the roof of the top portion of the left culvert is also eroded, but not nearly as much as the comparable location on the right side. An area of concrete a couple of square feet and about two to three inches deep on the roof a few feet downstream from a construction joint was eroded.

The purpose of this study was to determine if the hydraulic conditions are significantly different from those anticipated during the design process and if these hydraulic conditions are causing the damage to the crossover roof. This involved first discussing operations with project personnel, and then evaluating the pressures and velocities in the troubled area where the concrete has failed and also in other sensitive areas of the filling and emptying system such as just downstream of the valves. There was concern that adverse conditions (pressures) are occurring near the damaged area on the top portion of right crossover.

Previous Investigations

A 1:25-scale lock model study was reported by Ables (1978). The model reproduced approximately 700 ft of the upstream approach, the entire filling and emptying system, and about 600 ft of the downstream approach. Piezometers were placed at points throughout the filling and emptying system culverts. The piezometers, which provide average pressures, were read during lock operations. Pressure cells were used to measure instantaneous pressures at selected locations in the culvert system and to record water surface in the lock chamber. The model study provided pressure data and lock filling and emptying times for various valve operations. Particular emphasis was given to valve operations and the resulting pressures in the culvert immediately downstream.

McGee (1989) conducted a field investigation to determine the operating characteristics and hydraulic efficiency of the lock. Particular attention was given to evaluating important design factors such as the cavitation parameter and the effects of venting and submergence of the valves. Pressure transducers were used to measure the water-surface elevation in the upper pool, the lock chamber, the lower pool, and the left filling and emptying valve wells. Transducers were also mounted on the left culvert roof to measure the piezometric head downstream of the filling and emptying valves.

Approach

The filling and emptying system of Whitten Lock was evaluated using the one-dimensional (1D) unsteady flow model LOCKSIM (Schohl 1999). The approach taken was to construct a model of the Whitten Lock system and then investigate hydraulic conditions with various operational schemes for both filling and emptying. The idea was to minimize the differential pressure at the culvert roof in the crossover area while maintaining acceptable hydraulic conditions throughout the remainder of the culvert system. The differential pressure is the internal pressure exerted on the soffit of the culvert roof less the hydrostatic pressure exerted on the culvert top produced by water in the lock chamber.

Model Validation

The numerical model reproduced the entire filling and emptying system including the intakes, filling and emptying valves and valve wells, culverts, filling and emptying manifolds, lock chamber, and outlets. Field data reported in McGee (1989) were used to determine energy loss coefficients on the components. These data include pressures downstream of the filling valves, the water surface in the valve wells and the lock chamber. Loss coefficients for many hydraulic components are well established and are readily available in the literature (e.g. Miller 1990). However, lock culvert system components are often unique to a particular project and the loss coefficients have not been determined. This study validated the model using field data to refine loss coefficient values. These coefficients were then used in modeling existing operation conditions and to investigate alternative valve operation strategies. The model results for a filling test are compared with those observed in the field on Figure 2. The valve opened in 219 sec and the lock filled in 10.4 min. The maximum drawdown in the well was to el 370. The lowest pressure observed in the field in the culvert downstream of the filling valve was el 305.3; whereas, the model computed a minimum elevation of 301.3. The lowest pressures occur at 110 sec when the valve is about 35 percent open. The model reproduces the field data quite well except for the pressures downstream of the filling valve when the pressure is lowest. However, the model is conservative since its predictions are lower than field measurements.

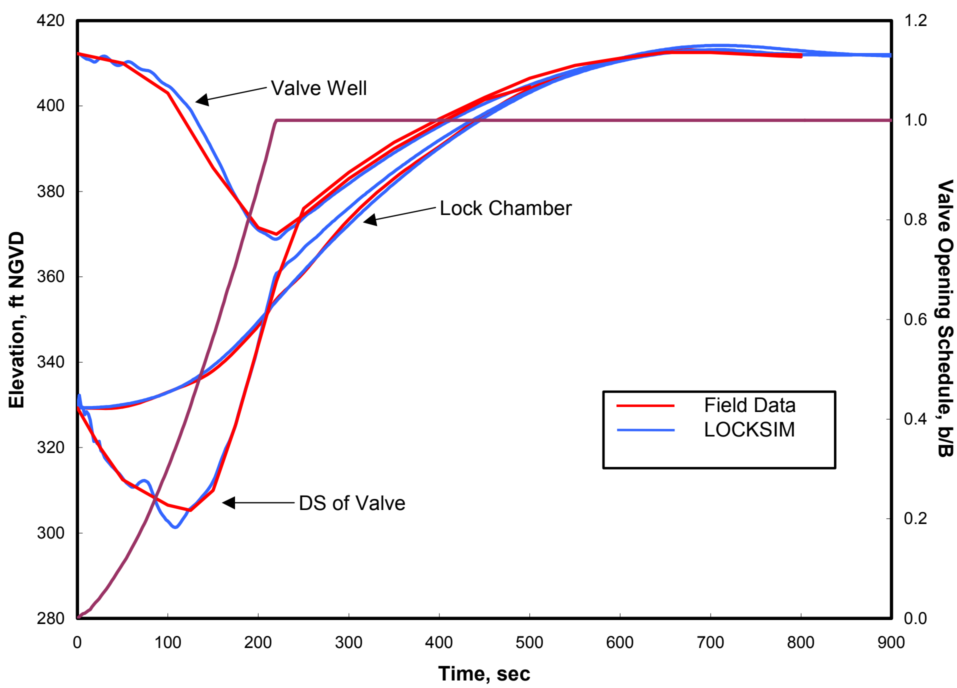

Figure 2. Model and prototype comparison of conditions during filling

The emptying system was validated using a test in which the valve operated in 205 sec. The emptying system model results are provided in Figure 3. The water-surface curve shows that the lock emptied in 11.8 min. The computed emptying curve matched the field data well. The time variation of the well's water surface reduces significantly at 220 sec. The lowest pressure measured was el 308.5; whereas, the lowest elevation computed by the model was el 306.7. The lowest pressures downstream of the valve occur when the valve is 50 to 70 percent open. The model is conservative in estimation of pressure downstream of the valve. The model with the loss coefficients determined from the field data for filling and emptying was considered adequate for the present study.

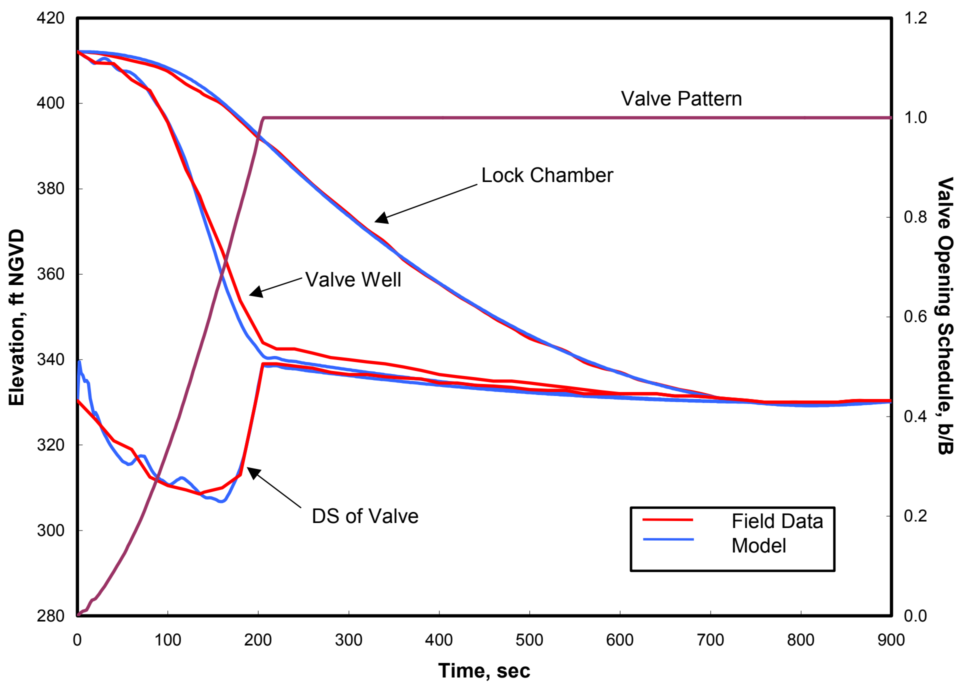

Figure 3. Model and prototype comparison of conditions during emptying

Existing Operations

Operation conditions presently used at the project were modeled to evaluate the existing hydraulic conditions throughout the system. The design lift of 84 ft was simulated. The valve operation times of 135 sec for both the filling and emptying valves were supplied by project personnel. Both normal- and single-valve filling and emptying operations were modeled.

The results of these calculations are shown on the time history plots in Figure 4.

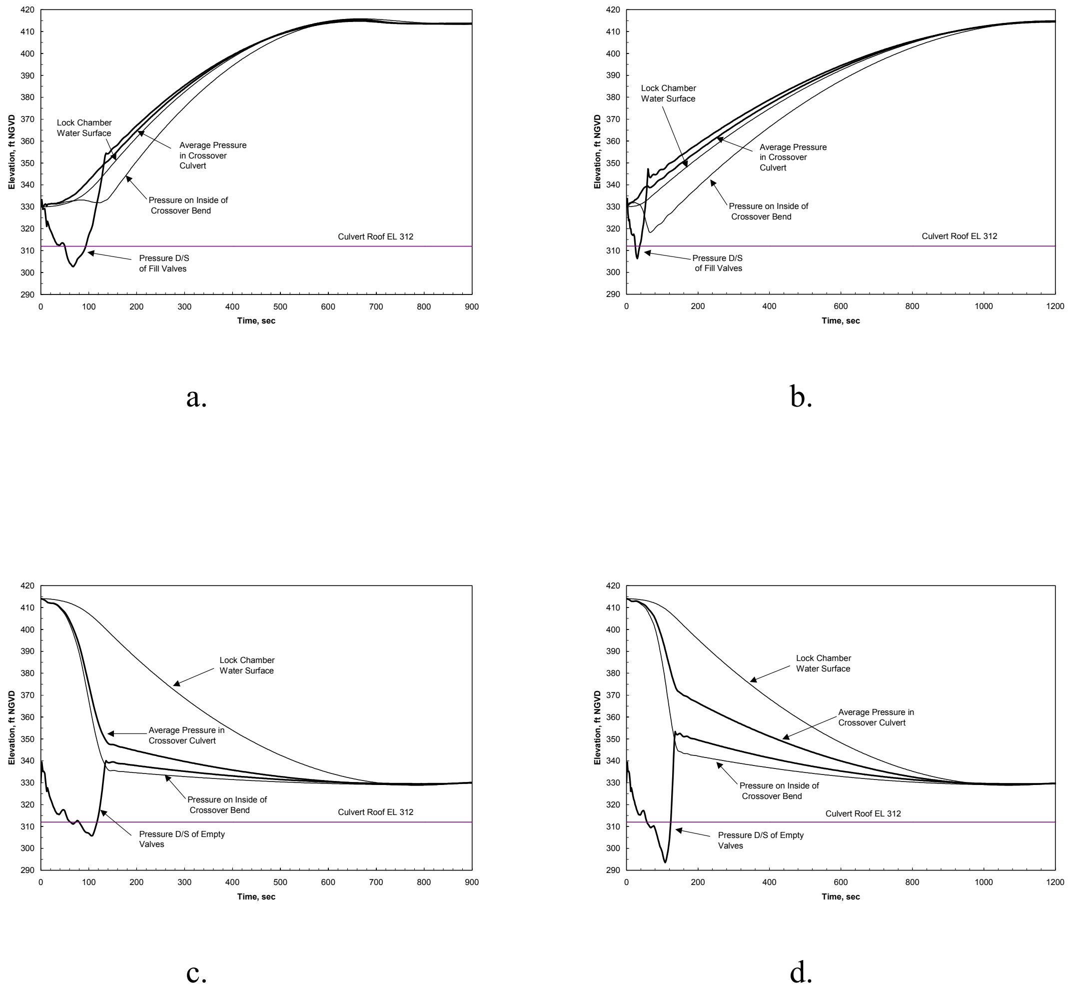

Figure 4. Lock filling and emptying characteristics at design lift: a. Normal-(dual) valve filling, b. Single-valve filling, c. Normal-valve emptying, d. Single-valve emptying

Pressures are a minimum on the inside of the crossover bends where velocities are a maximum. Estimations of the pressures on the inside wall are determined from the cross-sectional average velocity and pressure within the cross-over culvert (U.S. Army Corps of Engineers 1952)

$$h_{pi} = h_p - C_p \frac{V^2}{2g}$$

where h_p = cross-sectional average pressure head, h_{pi} = pressure head on the inside of the bend, C_p = pressure drop parameter, V = cross-sectional average velocity, g = gravitational acceleration. The bend pressure coefficient is a function of the culvert's radius of curvature and culvert half-width. The C_p value for the culvert bends found on the Whitten Lock crossover is 0.48. So, the pressure head difference between the cross-sectional average and that on the inside of the bend is about half (0.48) of the average velocity head in the culvert.

Three-Dimensional Model

To further investigate the flow field inside the culverts, a three-dimensional (3D) flow model, ADH (Stockstill and Berger 2000), was constructed of the right filling culvert and crossover culverts. The idea was to use the 3D model results as a flow visualization aid. The 3D finite element mesh is depicted in Figure 5. Peak flow conditions during normal-valve filling (138 sec into filling operation) were extracted from the 1D model results and imposed as boundary conditions to the 3D model. Velocity distributions are illustrated using flow ribbons (Figure 6). Figure 7 shows the pressure contours on horizontal planes passing through the center of the upper and lower crossover culverts. These plots are the pressure head relative to the culvert roof elevation (el 312). The pressure contours show significantly lower pressures on the inside of the bend and higher pressures on the outer wall of the bend. The pressure distribution across the culvert suggests that if cavitation led to the concrete failure, it would have most likely have occurred on the inside wall rather than in the center of the culvert roof.

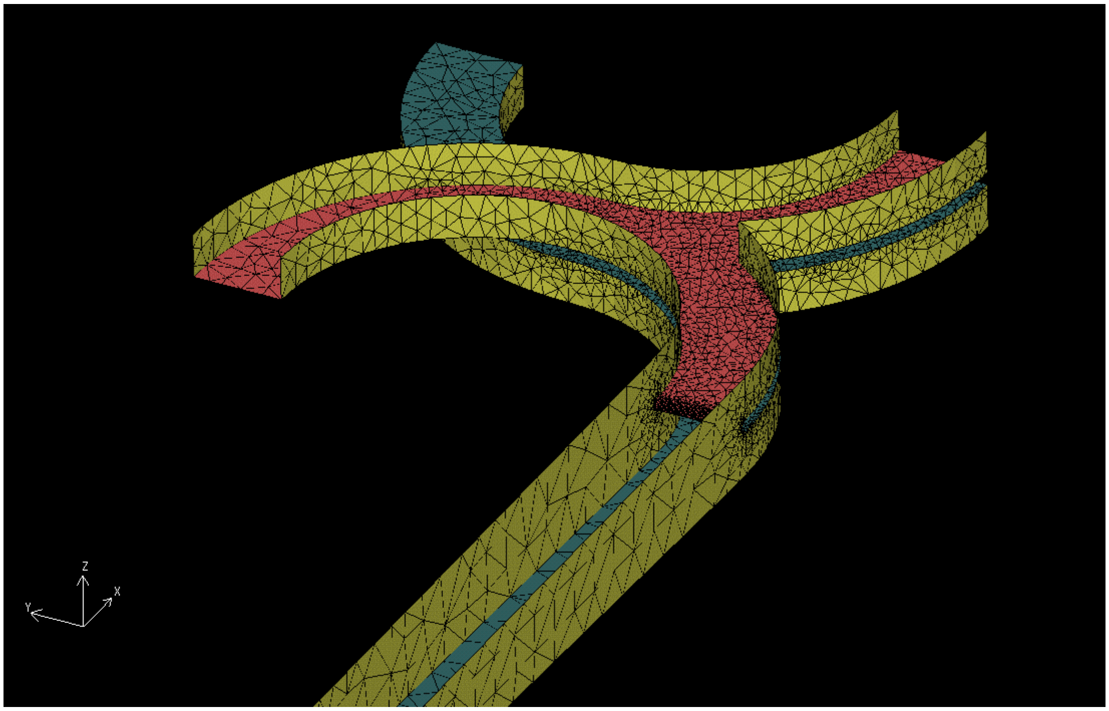

Figure 5. Surface mesh of 3D model of crossover culverts (top removed)

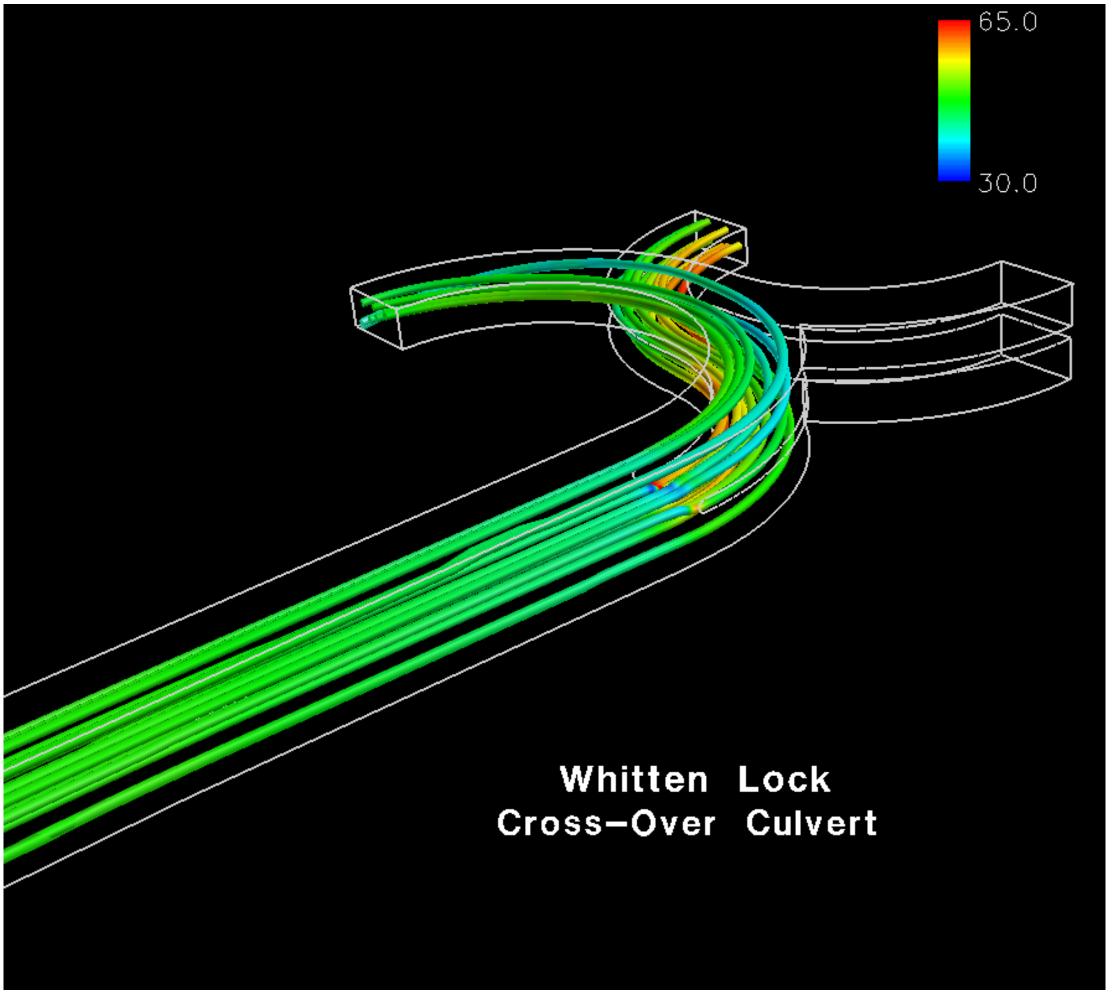

Figure 6. 3D model results, flow lines within the crossover culverts at peak lock filling discharge

Conclusions

This evaluation of the Whitten Lock has determined that the hydraulic conditions within the filling and emptying system for the normal operations indicated by project personnel are not much different that what was anticipated during design. The differential pressure across the culvert roof at the area of concern is larger for longer valve times during filling, and actually reduces as valve times are increased during emptying. There is not significant difference in the resultant pressure in the crossover for normal- or single-valve during filling operations. However, the normal-valve produces a much larger resultant than a single-valve during emptying. This differential pressure would produce the bending moments on the roof. The numerical model shows that the prototype experiences a maximum differential of 52 ft m across the culvert roof during a 2-min normal-valve emptying operation. The physical model study (Ables 1978) reported differences of about 58 ft in this area under these same operating conditions. This leads to the conclusion that the hydraulic conditions in the existing project are similar to those expected during the design phase.

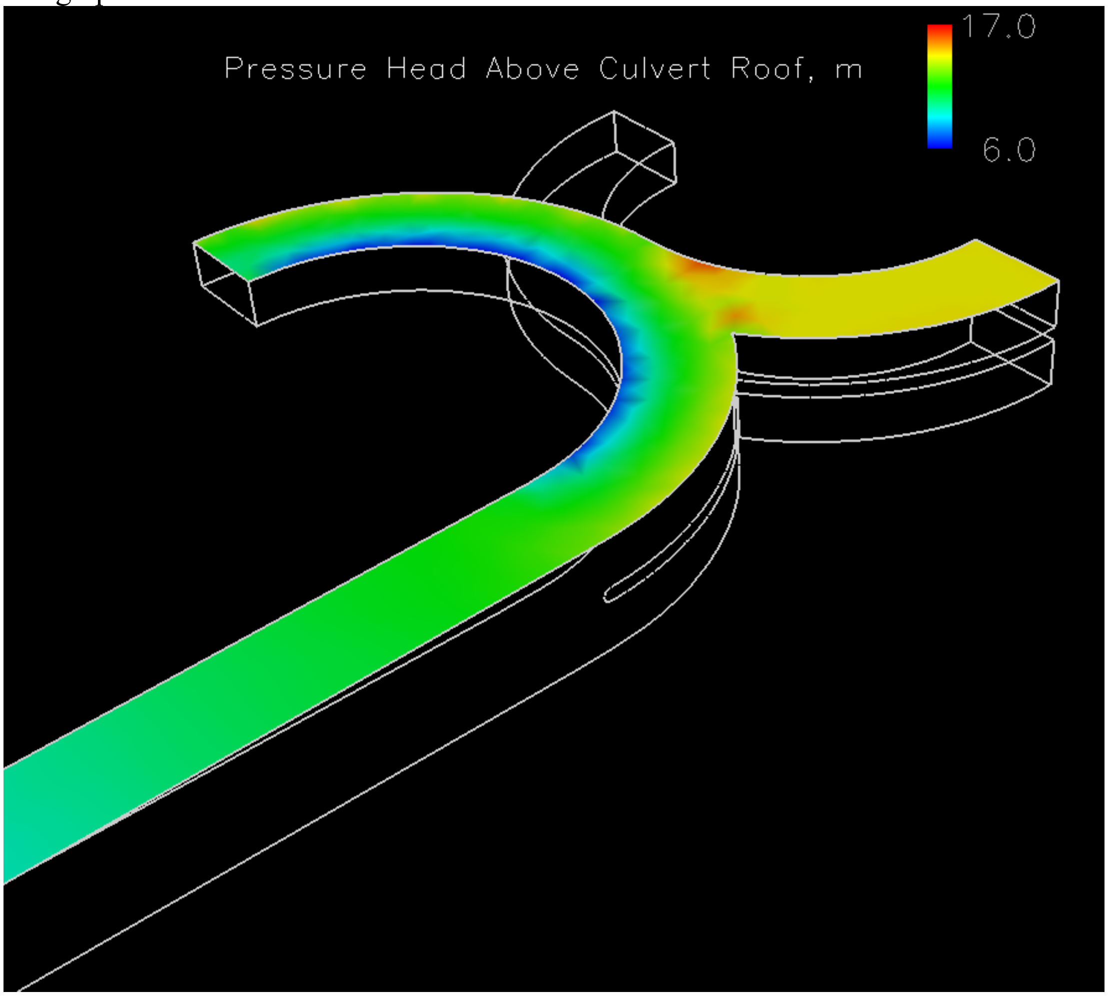

Figure 7. 3D model results, pressure contours on roof of crossover culverts at peak lock filling discharge

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